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EFFECT OF TEMPERATURE ON MOVEMENT OF WATER VAPOR AND CAPILLARY MOISTURE IN SOILS

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INTRODUCTION

An investigation of the influence of temperature on the various physical processes in the soil was undertaken by the writer at the Michigan Agricultural Experiment Station. One of the phases of this investigation, the effect of temperature on the movement of water vapor and capillary moisture in soils, will be considered in the present paper.

MOVEMENT OF MOISTURE FROM WARM TO COLD COLUMN OF SOIL OF UNIFORM MOISTURE CONTENT

A rise of temperature decreases both the surface tension and the viscosity of water to the extent shown by the data in Table I.

TABLE I.—*Relation of temperature to the surface tension and viscosity of water*

Temperature.	Surface tension.	Viscosity.
°C.		
0	100.00	100.00
10	97.96	73.32
20	94.32	56.70
30	91.62	45.12
40	88.46	36.96
50	85.52	30.17

It will be noted that the degree of diminution with rise in temperature is considerably greater in the case of viscosity than in that of surface tension.

During the warm part of the year the soil at the upper depths maintains a rather marked temperature gradient which reverses itself between day and night to the depth that the diurnal amplitude of temperature oscillation extends. This diurnal change of temperature gradient occasions an alteration in surface tension and viscosity of the soil moisture, the amount depending upon its variation at the different depths. Since capillary action is said to depend upon surface tension and facility of movement upon viscosity, there should occur an up-

ward and downward movement of moisture as the temperature gradient changes diurnally. During the day, for example, the temperature of the soil is highest at the surface and diminishes with depth; the surface tension and the viscosity of soil moisture are lowest at the surface and rise with depth; consequently, the movement of moisture should be downward. During the night the reverse is true; the soil temperature is lowest at the surface and increases with depth; the surface tension and the viscosity of the soil water are greatest at the top and diminish downward with increase of temperature; hence, the water translocation should be upward.

These considerations are *a priori* deductions from the laws of surface tension and viscosity in their relation to temperature. Whether or not

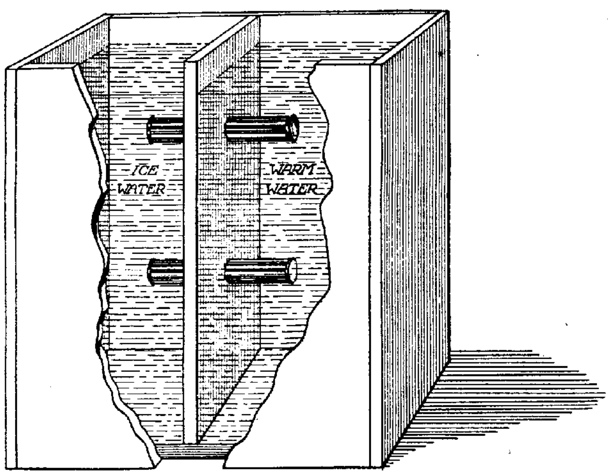

FIG. 1.—Apparatus for determining thermal translocation of soil moisture when the column of soil lay horizontally.

they are valid, however, has heretofore not been known, since there appear to be no experimental data bearing directly upon the subject.

With the object of obtaining this important and much desired information, an investigation of the problem was undertaken. The general method of procedure consisted of placing soils of different but uniform moisture content in brass tubes 8 inches long and 1½ inches in diameter, closing both ends with solid rubber stoppers, and keeping one half of the soil column at a high temperature and the other half at a low temperature for a certain length of time, then determining the percentage of moisture of the two columns and attributing any difference in water content to thermal translocation. There were only two amplitudes of temperature employed, 0° to 20° and 0° to 40° C.—i. e., one half of the soil column was kept at 0° and the other half at 20° and

40° C. For producing these temperature amplitudes wooden boxes were used which contained melting ice and warm water in separate boxes or compartments the temperatures of which were maintained constant by the addition of ice and hot water, respectively.

The movement of moisture from warm to cold soil was studied in two different ways: (1) When the column of soil lay horizontally and (2) when it stood vertically. For the first case, the wooden boxes used were 22 inches long, 10 inches wide, and 20 inches deep, having wooden partitions in the center which contained perforations of the size to fit the tubes (fig. 1). One compartment contained melting ice and the other water at the required temperature. To prevent any exchange of water between the two compartments, the edges of the partition and the

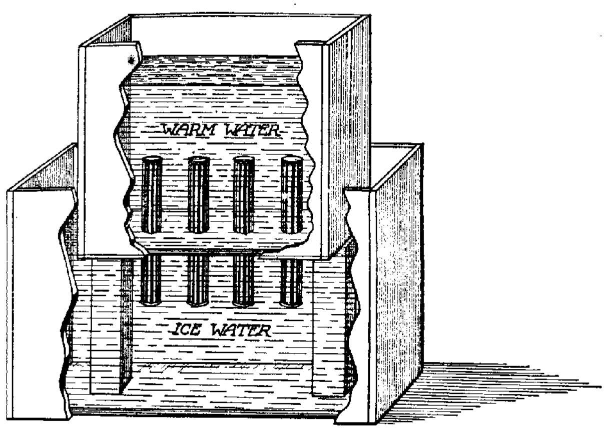

FIG. 2.—Apparatus for determining thermal translocation of soil moisture when the column of soil stood vertically.

holes through which the tubes passed were made water-tight by means of paraffin.

For the second study, the employment of two boxes was necessary (fig. 2). One box, which contained melting ice, was 24 inches long, 10 inches wide, and 13 inches deep. The other box, which contained water at the desired temperature, was 13 inches long, 7 inches wide, and 11 inches deep, and was placed inside the first box. The bottom of the small box was supplied with holes the exact size of the tubes, which were then placed in the holes and the crevices surrounding them sealed with melted paraffin to make the small box waterproof. The inner box was then put upon supports in the large box and was filled with water kept at the desired temperature. The outer box was filled with ice up to and touching the bottom of the inner box. All the boxes were well insulated, and since they were big and contained large volumes of water, the temperature could be kept to within small variations for long

periods. The water was stirred occasionally to maintain uniformity of temperature throughout its mass.

The temperature amplitudes employed are within the upper limit of the diurnal amplitudes of temperature at the upper depths in the soil, but they are too high for the range of temperature that exists at any one time between the various adjacent depths.

The duration of each experiment was about eight hours. This time limit was calculated to represent approximately the length of period that the day and night soil temperature gradient is most marked.

The effect of temperature on the movement of moisture in soils of uniform moisture content was investigated in five diverse classes of soil: Miami light sandy loam, Miami heavy sandy loam, Miami silt loam, Clyde silt loam, and Miami clay. Each soil contained a large number of different moisture contents. These various moisture contents in each soil ranged from very low to very high.

To procure a very uniform moisture content throughout the soil column, each soil, after it was moistened to the desired degree, was passed through a sieve and then mixed thoroughly. It was then placed in the tubes and packed uniformly by allowing the tubes to fall in a vertical position from a certain height a definite number of times.

At the end of each experiment the warm column was separated from the cold column of soil by means of a spatula. This was done by drawing out all the soil from that warm section of the tube which extended up to the plane of the partition and allowing for the cold column all the soil that was contained in that cold section of the tube up to the other plane of the partition, and also that portion of the soil contained in the tube under the hole of the partition. This last part of the soil was accorded to the cold column of soil because its temperature is intermediate between the opposite temperature extremes, and it was desired to make the lines of demarcation between the two columns of soil as prominent and distinct as possible. The moist soils were dried in an electrical oven for about 20 hours at a temperature of 105° C., and the percentage of moisture content was calculated on the dry basis. The weights were always determined on a sensitive chemical balance.

The fact has been mentioned that the movement of moisture from a warm to a cold column of soil was studied in two different ways: (1) When the column of soil lay horizontally and (2) when it stood vertically. The data obtained from both series of experiments show that if the same percentages of moisture were employed practically the same results would be obtained, no matter whether the soil columns remained in the horizontal or vertical position. For the sake of brevity and simplicity of presentation, therefore, only the results of the series of experiments wherein the soil column was held in the vertical position will be presented here. These experimental data, together with their diagrammatic representations, are submitted below. Table II gives the

various moisture contents of the different soils and the percentage of moisture moved from the column of soil at 20° to the column of soil at 0° and from the column of soil at 40° to the column of soil at 0°. The percentage of moisture moved represents the difference between the percentages of moisture found in the cold and the warm columns of soils, respectively, at the end of the experiment; at the beginning of the experiment the moisture content was the same in both columns of soil. Figure 3 represents these data in a graphical form.

TABLE II.—*Movement of moisture from a warm to a cold column of soil of uniform moisture content*

Kind of soil.	Percentage of moisture in soils.									
Sandy loam:										
Beginning of experiment	2.29	3.86	6.45	7.50	8.48	9.95	10.94	13.75	15.96	......
Movement from 20° to 0° C	.102	.296	.792	.900	.530	.520	.466	.340	.100	......
Movement from 40° to 0° C	.410	1.064	1.97	2.882	1.715	1.467	1.30	.97	.30	......
Heavy sandy loam:										
Beginning of experiment	4.20	6.52	9.08	10.42	12.43	14.02	16.03	......	......	......
Movement from 20° to 0° C	.160	.631	.930	.721	.582	.491	.21	......	......	......
Movement from 40° to 0° C	.59	1.75	3.02	2.40	1.98	1.40	.42	......	......	......
Silt loam:										
Beginning of experiment	4.29	8.06	9.76	11.28	14.441	15.95	17.63	19.30	21.42	23.51
Movement from 20° to 0° C	.138	.736	1.024	1.180	1.190	1.10	.85	.48	.35	.21
Movement from 40° to 0° C	.471	1.98	2.65	3.276	3.68	3.58	2.60	1.75	1.02	.45
Clyde silt loam:										
Beginning of experiment	7.56	12.51	14.98	17.59	18.80	21.55	22.76	29.98	34.57	......
Movement from 20° to 0° C	.122	.46	.89	.96	1.07	.99	.83	.62	.20	......
Movement from 40° to 0° C	.409	1.72	2.07	2.45	3.27	2.82	2.30	1.36	.51	......
Clay:										
Beginning of experiment	9.70	18.38	19.29	20.69	22.98	29.88	......	......	......	......
Movement from 20° to 0° C	.248	.72	.99	.73	.70	.681	......	......	......	......
Movement from 40° to 0° C	.672	2.60	3.29	2.50	2.12	1.88	......	......	......	......

The foregoing data present many important and remarkable facts. First of all, they show most emphatically that the *a priori* prediction regarding the thermal movement of moisture as deduced from the laws of surface tension and viscosity in their relation to temperature is not strictly realized. According to these laws, the amount of water moved from a warm to a cold column of soil should be the same for all moisture contents, provided the soil mass exerts no influence upon water; inasmuch, however, as the soil does exert an adhesive force upon water, the thermal translocation of moisture should increase with a rise in water content. Instead, the percentage of water moved from a warm to a cold column of soil at both temperature amplitudes increases regularly and rapidly with an increase in moisture content in all the different types of soil until a certain moisture content is reached, and then it begins to decrease with a further rise in the percentage of water. The results then plot into a parabola, with a maximum point instead of a straight line. This maximum point of water thermal translocation is significant in at least two ways: (1) It is quantitatively about the same for all classes of soil and qualitatively the same for both amplitudes of temperature; and (2) it is attained at entirely different moisture contents in the various soils and at a comparatively low percentage

of moisture. On referring to the data in Table II it will be seen that the maximum thermal water transference at the amplitude of 20° C. is 0.90 per cent for light sandy loam, 0.93 for heavy sandy loam, 1.19 for silt loam, 1.07 for Clyde silt loam, and 0.99 for clay; at the temperature amplitude of 40° it is 2.88 per cent for light sandy loam, 3.02 for heavy sandy loam, 3.68 for silt loam, 3.27 for Clyde silt loam, and 3.29 for clay. It should be noted that the percentage of thermal

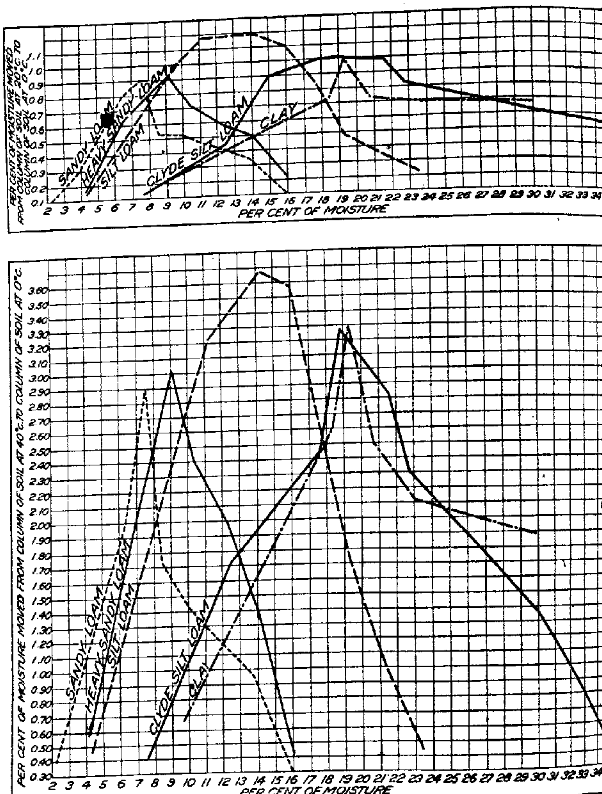

FIG. 3.—Curve showing the movement of moisture from a warm to a cold column of soil of uniform moisture content.

motion of water increases more than proportionally with temperature. The temperature of 40°, for instance, is only twice as great as 20°, while the percentage of moisture moved is three times greater in the former case than in the latter. The water content of the various soils at which the maximum thermal translocation occurs is 7.50 per cent for light sandy loam, 9.08 for heavy sandy loam, 14.21 for silt loam, 18.80 for Clyde silt loam, and 19.29 for clay.

Obviously, then, the maximum thermal water movement depends upon a definite condition of moisture of any particular soil; a deviation from this definite degree of moisture in either direction causes a decrease in thermal movement of water. Since this definite percentage of moisture at which the greatest quantity of water is able to move from a warm to a cold column of soil appears to be a specific constant or characteristic of the various soils, it is proposed to designate it as "thermal critical moisture content." A thermal critical moisture content may be defined, then, as that percentage of moisture in soil which allows the greatest amount of water to move from warm to cold soil at any amplitude of temperature.

A further examination of the preceding experimental data shows that the thermal movement of moisture is extremely sensitive to the amount of water present in a soil. It will be noted that by increasing or decreasing the percentage of soil water by small degrees, the thermal movement varies very markedly in either direction. From this it follows that the thermal critical moisture content must be quite definite, and in order to obtain it absolutely, the percentage of soil moisture near the point of maximum thermal movement must be increased by small amounts. This applies especially to the light sandy soils, in which the sensitiveness appears to be more marked and the range more limited. If the increase in percentage of moisture content took place in this soil by 0.1 instead of 1.0 per cent, the maximum thermal translocation would probably have been as high as that of the other soils. It is possible, however, that the value obtained is about the upper limit for this soil and consequently for all soils of its type.

The diminution of the thermal translocation of water with a decrease in moisture content from the point of thermal critical moisture content might be anticipated, but the decrease of water movement with further increase of moisture content after the point of thermal critical moisture content was not expected. Indeed, it was at first thought that the movement would be greater at the highest moisture content because there would also occur a gravitational movement. When soils contain as high as 35 and 30 per cent of moisture, as did the Clyde silt loam and the clay, respectively, and when one half of their column is kept at 40° and the other at 0° C. for eight hours, such expectation as the above is not at all unnatural. Instead, the water movement at these highest moisture contents is very low and in descending order and the cessation of diminution is not as yet reached. These results go to show, then, in a most striking manner that the soils possess a very great attraction for water and that their requirements for water to satisfy their attractive forces before free movement of water can take place are, indeed, high. Until the point is reached where gravitational movement occurs, the moisture in the soil is held by a force of great magnitude.

Now, the next question is, How may this peculiar thermal translocation of water be explained? What are the causal agents which bring it about?

As already stated, it is not entirely due to the surface tension and viscosity of the soil water, for if that were the case then the movement should have followed a different course. If the soil exerted no adhesive force for water, the amount of moisture moved from a warm to a cold column of soil should be the same for all moisture contents, provided the force of gravity is eliminated for any particular amplitude of temperature. But since the soil does exert a strong adhesive force for water, the thermal motion of water should follow a straight line with rise in moisture content for any given difference in temperature. Instead, the results plot into a parabola. Evidently there must be another explanation for the phenomena.

The best explanation suggested appears to be founded upon the following four assumptions: (1) The soil possesses an attractive power for water and holds it with a great adhesive force; (2) these attractive and adhesive forces decrease with increase in temperature; (3) the surface tension or cohesive power of the liquid also diminishes with rise in temperature; and (4) the force due to the curvature of the water films between the soil grains, which are known as capillary films, decreases with increase of water content.

All these four assumptions appear to be correct. The validity of the third and fourth is generally recognized and consequently needs no further discussion. The validity of the first is also universally accepted: That the soil possesses an attractive power for water can hardly be denied; that the soil holds the water with a great adhesive force is evidenced by the great difficulty experienced in attempting to separate the one from the other. Indeed, this adhesive force is so great that no method as yet has been devised either to execute a complete separation of the two components or to measure with any degree of precision its magnitude. The researches of Lagergren (8),[1] Young,[2] and Lord Rayleigh (10) indicate, however, that this force may be of an order of magnitude from 6,000 to 25,000 atmospheres.

The great attractive and adhesive forces which the soil exerts upon water are further illustrated by the researches of Briggs and McLane (3) on the moisture equivalent and by those of Briggs and Shantz (4) on the wilting coefficient of plants. By whirling wetted soils in a rapidly revolving centrifuge fitted with a filtering device in the periphery and developing a force equivalent on the average to 3,000 times the attraction of gravity, Briggs and McLane found that some clay soils would still contain about 50 per cent of water. The studies of Briggs and McLane on the wilting coefficient of plants show that plants would wilt and die in clay soils even

[1] Reference is made by number to "Literature cited," p. 172.

[2] Cited by Minchin, G. M. Hydrostatics and Elementary Hydrokinetics, p. 311, London, 1892.

when the moisture content was still about 30 per cent. As the water content increases, these attractive and adhesive forces decrease.

Of all the four assumptions the correctness of the third—namely, that the attractive and adhesive forces decrease with temperature—may be doubted by many and challenged by a few. The theoretical and experimental evidences, however, are overwhelmingly in its favor. According to the law of kinetic energy, the attractive and adhesive forces of solids for liquids and gases or vapors should decrease with rise in temperature. The investigations upon the absorption of gases and vapors at different temperatures show this to be the case. The work of De Saussure (11) and Von Dobeneck (6) upon the absorption of gas by different solid materials, and the researches of Knop[1] and Ammon (1) upon the absorption of water vapor by soil, seem to show conclusively that the absorptive power of diverse solid materials for gases and water vapor decreases with increase in temperature. The only evidence which is contrary to the above is that obtained by Hilgard (7, p. 198) on the absorption of water by dry soils from a saturated atmosphere. Hilgard's results show that the absorption of water vapor by soils increases with rise in temperature. The results obtained by the several investigators mentioned, as well as new evidence which will subsequently be presented, tend to throw considerable doubt on the correctness of Hilgard's data. Hence, it can safely be asserted that the third assumption is correct.

Bearing these postulates in mind, the phenomena of thermal water translocation observed may be explained as follows: The soil with the lowest moisture content holds the water with a force of great magnitude. When the temperature of a column of this soil is uniform throughout, the adhesive and attractive forces are at an equilibrium. When one half of this column of soil is heated to 40° and the other half to 0° C., this equilibrium is disturbed. The attractive and adhesive forces of the soil for water and the cohesive power or surface tension of the soil water are decreased in that portion of the soil column which is maintained at 40° and increased to a corresponding magnitude in that portion of the soil column which is kept at 0° C. The cold column therefore exerts a pull and draws water from the warm column in amount depending upon the quantity that the latter is willing to give up. Since the soil possesses a great attraction for water, which attraction varies with the diverse classes of soil, and inasmuch as this attractive force is not satisfied at the low moisture content, the warm soil parts only with a small amount of its water. Hence, the amount of water moved from the warm column to the cold column of soil is small.

At the next higher moisture content the attractive power of the soil for water is further satisfied and the total water content is held with less force. When a column of this soil is kept at the same amplitudes of temperature as above, the decrease and increase of the adhesive

[1] Cited by Johnson, S. W. How Crops Feed. p. 164. New York [1870].

and cohesive forces, due entirely to temperature, between the warm and cold columns of soil are equal in amount, as in the soil with the lowest moisture content. Water, therefore, tends to move from the warm to the cold soil. Inasmuch as the attraction of the soil has been further satisfied and the water films further thickened, the pull of the cold soil, due only to the attractive forces of the soil for water, is decreased; on the other hand, the ease with which the warm soil gives up moisture is increased. The result is that even though the total effective pull (composed of the increased surface tension of water, the increased attractive adhesive forces of soil for water, and the force of the curvature of the capillary films) of the cold soil with the high moisture content is less than that of the soil with low moisture content, the greater ease with which the warm soil with high water content parts with moisture enables the reduced effective pull to draw more water from the warm to the cold side. As the moisture content of the soil is continually increased, its attractive power is satisfied and the curvature of the capillary films decreased correspondingly. The total effective pull of the cold column of soil is continually decreased, but the ease with which the warm column of soil gives up moisture is also continually increased, so that the thermal translocation of water is constantly increased with rise in moisture content.

Finally, a degree of moisture content is reached in which the effective pull of the cold column of soil is able to extract the greatest amount of water from the warm column of soil. This degree of water content is the thermal critical moisture content. At this point the attractive power of the soil for water is considerably satisfied but is far from being entirely appeased; the total effective pull of the cold column of soil is also considerably less than that of the preceding columns of soil, but the warm column yields water to this pull with such ease that there occurs a maximum thermal water translocation. Inasmuch as the water-attractive power is different for the various kinds of soils, this thermal critical moisture content is of necessity also different. After this thermal critical moisture content is reached, the effective pull of the cold column of soil is further decreased with a continued increase of moisture content. And although the willingness of the warm column of soil to part more readily with moisture is also increased, yet the pull of the cold column of soil is not sufficiently strong to draw it; consequently the thermal movement of water commences to decrease and continues to diminish very regularly and gradually with a continued increase in moisture content. When the highest percentage of water is reached, the warm soil is very willing to part with a very large amount of water, but since the effective pull of the solid soil is reduced almost to a minimum, only a small amount of moisture is drawn from the former to the latter.

The degree of moisture of the different soils could not be further increased, on account of the difficulty of sifting them, and consequently it

can not be stated with certainty whether the thermal movement of water would become zero at a still higher moisture content. From the theoretical point of view, however, it should not become zero, because the pull due to the surface tension of water alone is not affected by increase of moisture content, but remains constant. The portion of pulling force which is decreased constantly with a rise in moisture content is that pertaining to the attractive power of soil for water and to the curvature of the capillary film. At or near the point of saturation the pulling power due to these two factors is probably zero; at this point the soil may be considered to be passive. Any thermal movement of water that takes place at or near the point of saturation is to be attributed to the surface tension of the soil water. If this assumption is correct and if the percentage of moisture moved at the highest moisture contents employed is to be considered as a measure of the amount of thermal translocation due to surface tension of water alone, it will be found that the quantity due to this force is very small indeed. As will be seen from the experimental data, the percentage of moisture moved at both amplitudes of temperature is reduced to an insignificant value at the highest moisture contents.

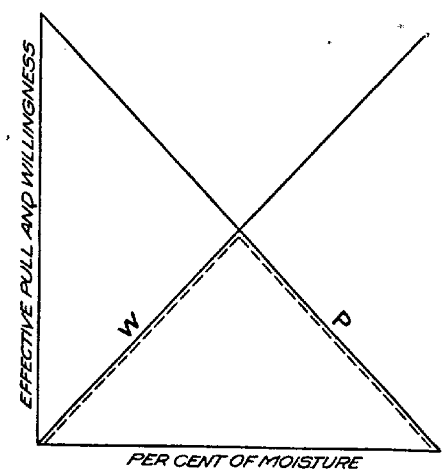

FIG. 4.—Diagram illustrating the cause and mechanism of moisture movement from a warm to a cold column of soil of uniform moisture content.

The foregoing exposition as to the cause and mechanism of the phenomena of thermal water translocation will probably be made clearer by figure 4. This diagrammatic representation, however, by no means pictures the real cause and mechanism absolutely and accurately, but it will serve, it is believed, to make clearer what has already been said.

Let the abscissa represent the effective pull of the cold column of soil and the willingness of the warm column of soil to part with water at a different moisture content, and let the ordinates represent the different percentages of water contained by the soil. By plotting the effective pull and willingness against the moisture content it will be seen that the effective pull decreases and the willingness increases with a rise in moisture content. At the point where the two lines cross probably occurs the

maximum thermal translocation of water. After this point of intersection the willingness of the warm soil to give up water is large, but since the effective pull is being reduced to a minimum the water is not moved. If a parabola is now drawn along the lines WP, with its maximum value at the point of intersection, then this theoretical curve will agree almost perfectly with the real one in figure 3.

The serious fault with the above illustration (fig. 4) is that the total effective pull tends to become zero, and theoretically this should not be the case, because while the pull due to the attractive power of the soil for water and to the curvature of the capillary films will ultimately become zero, the pull due to the increased surface tension of the soil water should not become zero, but should remain the same for all moisture contents. Hence, figure 4 illustrates more correctly only the thermal translocation of the water as due to all the other forces except the surface tension of water.

The next important question to consider is the mode and amount of thermal translocation of water in field soils as suggested by the foregoing laboratory experimental data. Under field conditions the soil moisture exists practically always in a gradient form. As the water content tends to decrease upward from the water level, the forces due to the curvature of the capillary film and to the attractive power of the soil for water increase correspondingly; consequently the pull is upward. The soil temperature also exists in a gradient form, but this reverses itself diurnally and therefore modifies these pulling forces. During the day the temperature at the upper depths is higher than that below; the attractive and adhesive forces of the soil for water and the surface tension of water are decreased, so that the total upward effective pull is diminished correspondingly. Inasmuch as the temperature below is less than that above, the effective pull due only to the increased attractive and adhesive forces of the soil for water and to the surface tension of the soil water should occasion a downward movement of moisture. Since, however, the water-attractive forces of the soil below are more satisfied than those of the soil above, the downward pull due only to the attractive adhesion and surface tension as increased by a lower temperature is very small in comparison with the upward pull. Hence, during the day the moisture movement is upward. During the night nearly all of the above forces act in a parallel direction and favor an upward movement. Therefore, the thermal movement of moisture in soils is always upward and never downward.

The extent to which moisture will move during the night from the warmer soil below to the colder soil above will depend (1) upon the soil temperature gradient—that is, upon the difference in temperature of the various adjacent depths—and (2) upon the gradient or amount of moisture content at the various depths. In the preceding series of

experiments the temperature amplitudes of 20° and 40° C. were employed. In nature, however, so large and sharp variations in temperature between adjacent depths never occur during the night; they do occur, however, at the upper depths between day and night. Soil-temperature investigations which are being conducted at this Station show that in the early morning, when the temperature gradient is most marked, the temperature of the bare mineral soils increases sometimes in the summer and fall at the average rate of about 2° or 3° for each inch of depth down to about 4 inches, and then this rate becomes less. In cropped soils, where the temperature remains more constant, this rate of increase of temperature with depth is still less. Hence, the amount of thermal translocation of water that would occur during a single night would be very small. On the other hand, the maximum thermal translocation of water obtained in the preceding series of experiments was procured from a column of soil with uniform moisture content. As will be shown subsequently, there is no doubt whatever that this maximum thermal translocation of water in the various soils would have been far greater if the moisture content of the cold column was less than that of the warm column of soil. In nature, as already mentioned, the moisture exists in a gradient form; consequently the movement of water is upward and the forces of the factors which cause this upward movement are increased during the night. Therefore, while the amount of thermal translocation of water during a single night in soils under field conditions may not be as great as that obtained in the foregoing series of experiments, yet it will be quite appreciable; and since the process is repeated, the sum of the translocation for all the nights during the vegetative season will probably be considerable.

The moisture content at which the maximum thermal translocation of water occurs, or what has been designated as the thermal critical moisture content, is very significant and needs further consideration. It would be of very great interest to know, for instance, the thickness of the water film around the particles at this degree of moisture. This thickness could be calculated if all the soil grains were solid and spherical. The particles of the soils used, however—and these are the commoner types of agricultural soils—are neither spherical nor solid. Nearly all the particles in agricultural soils can be said to be irregular in shape. Some of them are solid and enveloped with a colloidal coating; others are compound aggregates, or "crumbs," and are porous; and still others, mainly of the peat nature, are of a sponge structure and are necessarily porous. The particles of a soil or soils may be classified under two categories: (1) Particles which are solid and have only an external surface and (2) particles which are partly or wholly porous and possess both an external and internal surface. In the solid and cleaned surface particles the water film is spread over the surface, but the film of water

envelops theoretically the whole external surface of the solid particles coated with colloids, or the mineral floccules and the organic particles; and water also permeates their internal surface. The single solid mineral grains, which may compose the compound particles, may be cemented together in a way analogous to that found in a piece of sandstone, in which case the water exists only in the interstices and not as a complete film around each particle. Furthermore, whether the soil grains are solid or spherical or compound and porous the water film is not uniform in thickness over the entire inner surface of the soil mass, but thickens more at the capillary angles between the particles.

In view of these considerations, therefore, it was considered useless to attempt to compute the thickness of the film, as many investigators have done. Furthermore, in view of the nature of the soil particles, as discussed above, it does not appear strictly proper to define the capillary water in the soil as a thin film overspreading the particles and thickened into a waistlike form at their points of contact. Hence, a new definition of capillary water is needed.

If we are to accept the theory which has been used to explain the foregoing phenomena of thermal translocation of water, that the soil possesses a very great attraction for water, that this attractive force is different for various soils, that it decreases with a rise in moisture content, and that it is completely satisfied at a considerably high moisture content, then our present views concerning the movement of capillary water in moist soils need modification. The present theory regarding the capillary movement of water consists of an analogy from the rise of water in capillary tubes. The interstitial spaces of a soil mass are considered as forming channels analogous to capillary tubes and are often designated as bundles of capillary spaces. The capillary water is believed to exist as surface films around the particles and as capillary films in the capillary spaces between the particles, and its movement is said to depend entirely upon the curvature of the capillary films. When a dry soil, for instance, is well moistened and brought to equilibrium, the water films are thick and the curvature of the capillary films small, and there will be no further capillary attraction of water if this soil is brought in contact with water. If this soil is allowed to dry at the top, the surface films become thinner and the force of the capillary films increases in direct ratio with their degree of curvature; hence, there will be a pull of water from the thicker surface films and less curved capillary films below toward the surface.

It is obvious that with this theory of capillary movement of water the whole cause of the capillary movement of water in a moist soil is attributed to the curvature of the capillary films between the particles, and the moist soil is considered as being passive, inactive, and exerting no influence whatever upon the movement of water. Indeed, Briggs

and Lapham (2), in trying to explain the differences in capillary action in dry and moist soils, make the following statement:

> In a moist soil, however, we have quite another condition. A film of the liquid covers all the surfaces of the soil grains. Since this film, once established, is maintained in a saturated atmosphere, it follows that the solid air and solid liquid surface forces no longer play any part in the capillary movement, which is produced entirely by the air liquid surface force and is opposed only by the weight of the liquid column.

In view of this general belief, Briggs, as well as other investigators, has tried to alter the properties of the soil water by increasing its surface tension, etc., with the object in view of increasing its capillary action.

If it were true that as long as a thin film of water is maintained in a damp or slightly moist soil the soil material itself exerts no longer any influence upon the movement of capillary water, then the preceding theory might be true. But we have seen in postulate 1 (p. 148) that the soils, and especially those rich in colloidal material, possess a very great attractive power for water, that this attractive power is satisfied only at a considerably high moisture content, that as long as it is not satisfied the soils will continue to take up water, and that they hold the water with a force of great magnitude. In view of the considerations presented in this postulate, and in view of the fact that the preceding thermal movement of water appears to be controlled by the attractive forces of the soil for water, it seems wrong to consider the soil material in moist condition as a static, passive, inactive, and irresponsive skeleton upon which the liquid plays its rôle. The solid material in moist condition short of saturation is dynamic and not static in respect to moisture movement. Hence, the capillary movement of water should not be attributed entirely to the forces exerted by the curvature of the capillary films, but also to the forces exerted by the unsatisfied attractive power of the soil for water. When a moist soil, therefore, begins to lose water at the surface, two effects are produced: (1) The attractive forces of the soil for water are increased and (2) the curvature of the capillary films is increased. Both of these effects exert a pull on the moist soil below and tend to draw water to the surface. As to which one of these two forces exerts the greatest pull it is impossible to say, because there is no way of measuring them. It is certain, however, that the force resulting from the attractive power of the soil for water must be very considerable, and probably it is the predominant of the two.

It might be argued that the preceding phenomena of thermal translocation of water could be explained entirely by the film theory without having to resort to the conception of the attractive forces of the soil. Such contention, however, can not be maintained, first, because it can not be conceived that the tension of the capillary films is operative and effective at such high moisture contents employed and, second, because the fact remains, nevertheless, that the soil exerts a pull owing to its

attractive forces for water, as has been abundantly proved. Furthermore, if it is maintained that the attractive forces of the soil for water are satisfied as soon as the soil is merely damped, then why should the soil hold additional large amounts of water with such a great force that it is impossible to extract it with mechanical means? It seems reasonable, therefore, to believe that if the soil holds large amounts of water with a great force, it should attract or absorb it with a force of equal magnitude.

MOVEMENT OF MOISTURE FROM A MOIST AND WARM COLUMN TO A DRY AND COLD COLUMN OF SOIL WITH AN AIR SPACE BETWEEN THE TWO COLUMNS

In the preceding section the thermal translocation of water was considered as occurring as water-film phenomena. There is still another way in which this thermal movement of moisture might take place: By vaporization and condensation of soil water from a point of high temperature to a point of low temperature. It is well known that water undergoes a transformation into the vapor state upon the application of heat, and the quantity of liquid vaporized increases with a rise in temperature. One of the remarkable characteristics of aqueous vapor is its sensitiveness to heat, changing from a gaseous to a liquid state, and vice versa, with very small variations in temperature. An excellent paradigm of this latter fact is the relative humidity of the air at different temperatures.

Since the temperature gradient of the soil reverses itself during the night—that is, it increases with depth—it is believed that there is a rising of vapor or moist air from the warmer soil below to the colder soil above, where the moisture is condensed. As a manifest proof of this theory, the morning dew is cited. It is concluded, therefore, that a large part of the water movement in soils is due to this process.

There appear to exist no direct experimental data as to whether or not there really is a translocation of moisture in soil at night, due to upward movement of the moist warm air and the condensation of its moisture at the cold soil above. Practically all of our present knowledge upon the subject consists of theoretical deductions from practical observations.

With the object of obtaining experimental evidence upon the subject the following investigation was performed. Into brass tubes 8 inches long and 1½ inches in diameter was placed moist soil at one end and dry soil at the other and the two columns separated by an air space. This air space was one-fourth of an inch in height and 1½ inches in diameter and was produced by placing between the two columns of soil a ring of cork, the two sides of which were closed with wire gauze that acted as supports of the two soils and prevented their particles from coming in contact. The tubes were then placed horizontally in the boxes shown

in figures 1 and 2. That part of the tubes which contained the moist soil was kept at 20° and 40° and the part which contained the dry soil was maintained at 0° C. The experiment was allowed to run about eight hours. If during this period the dry and cold soil gained any moisture, it obtained it by the condensation of vapor which was produced at the warm and moist soil. Since the dry soil possesses a high absorbtive power for water, it was assumed that it abstracted the vapor from the air space and that this air space was thus prevented from attaining an equilibrium. Five different classes of soil were used: Quartz sand, Miami light sandy loam, Miami silt loam, Clyde silt loam, and Miami clay. The moisture contents employed for each soil were three: Low, medium, and high. The percentage of moisture moved from the warm and moist column of soil to the cold and dry column of soil represents the difference between the percentages of moisture found in the dry soil at the beginning and end of the experiment. The results obtained are presented in Table III.

TABLE III.—*Movement of moisture from a warm and moist column of soil to a cold and dry column of soil, with an air space between the two columns*

Kind and temperature of soil.	Percentage of moisture in soil.		
Quartz sand:			
At beginning of experiment	2.90	6.83	13.52
Movement from moist column at 20° to dry column at 0° C.	.051	.046	.048
Movement from moist column at 40° to dry column at 0° C.	.286	.280	.294
Sandy loam:			
At beginning of experiment	7.23	10.27	15.82
Movement from moist column at 20° to dry column at 0° C.	.0238	.0313	.0246
Movement from moist column at 40° to dry column at 0° C.	.211	.253	.223
Silt loam:			
At beginning of experiment	9.16	14.52	16.40
Movement from moist column at 20° to dry column at 0° C.	.024	.033	.0273
Movement from moist column at 40° to dry column at 0° C.	.278	.273	.288
Clyde silt loam:			
At beginning of experiment	9.85	15.51	22.39
Movement from moist column at 20° to dry column at 0° C.	.028	.031	.040
Movement from moist column at 40° to dry column at 0° C.	.16	.22	.28
Clay:			
At beginning of experiment	10.77	15.36	20.35
Movement from moist column at 20° to dry column at 0° C.	.08	.06	.09
Movement from moist column at 40° to dry column at 0° C.	.18	.36	.26

The results in Table III show the most surprising fact that the amount of moisture moved from the moist and warm column of soil to the dry and cold column of soil by vapor is very insignificant. It will be seen that at the temperature amplitude of 40° the quantity of moisture moved is only about 0.25 per cent, and at the amplitude of 20° the value is only about 0.035 per cent. In comparison with the results of Table II, where it is shown that the maximum thermal movement of water at the thermal critical moisture content, when the soil mass is continuous, runs as high as 3.68 per cent in some cases, the above values, due only to vapor movement and condensation, are extremely insignificant.

From these results then it is safe to conclude that the thermal movement of moisture due to distillation is practically negligible, even at such high amplitudes of temperature as 20° and 40° C., which never exist during the night at the different depths on the soil, nor during such a long, continuous period as eight hours. This conclusion is indirectly substantiated by the studies of Buckingham (5) on the loss of soil moisture by direct evaporation from points below the surface. By exposing a surface of water or moist soil to evaporation into a confined space which was in communication with the outside air through a column of soil, Buckingham found that the actual mean rate of loss of water through diffusion of water vapor through soils in still air was very small.

Another noteworthy fact in the foregoing experimental data is that the amount of distillation from moist and warm to the dry and cold column of soil is the same for all moisture contents. This might have been anticipated, since the amount of water vaporized depends principally upon the temperature and is not governed by the amount of water present. On the other hand, if the amount of water present in the soil is extremely small, the water is held by the soil grains with an attraction of great magnitude, causing a lowering of the vapor pressure of the absorbed water film and thereby producing a diminution in the rate of evaporation. Perhaps the water contained in the soil with the lowest moisture content was above the point where this lowering of vapor pressure occurs; and consequently the partial pressure of the vapor in the air space in this soil was the same as in the air space of the soil with the greater moisture contents. Furthermore, the values are so small as to lie within the experimental error, and the method of moisture determination may not be sufficiently sensitive and accurate to show any decreased evaporation by the soils with the lowest moisture content.

In undertaking and performing the foregoing series of experiments it was taken for granted that there really is an upward movement of moist air during the night from the warmer soil below to the colder soil at the surface, where its vapor is condensed. This theory seems to be now very widely accepted, as already stated. The formation of the dew

is attributed by many writers almost entirely to this thermal movement of vapor. Thus, in discussing the subject Hilgard (7, p. 307) states that "dew is formed from vapor rising from the warmer soil into a colder atmosphere, and condensed on the most strongly heat-radiating surfaces near the ground, such as grass; leaves, both green and dry; wood; and other objects first encountering the rising vapor." Farther on he says: "The fact that dew is most commonly derived from the soil could have been foreseen from the other fact, long ascertained and known, that during the night the soil is as a rule warmer than the air above it." Other writers, such as Ramann (9), etc., claim in substance the identical belief.

But really, is there a rising of vapor or warm moist air from the warm soil below to the cold soil above? And is the source of water of the dew ascribable to this soil vapor? During the day the soil receives its heat at the upper surface, and its temperature rises. The heat is conducted downward, and the temperature of the various depths of the soil increases correspondingly. The temperature at the surface continues to increase until a maximum is reached and then begins to decrease. As the temperature increases and moves downward, the soil air expands, and as the volume of the pore space remains constant, it is expelled into the atmosphere. The pressure of the soil air at the different depths tends to be the same at any one time and equal to the atmospheric pressure, provided the communications are ideal. When the temperature at the surface soil is at the maximum, it is generally many degrees higher than that of the air above, amounting sometimes to 30° C. In fact, the air temperature decreases in calm and clear weather with an increase in height at the adiabatic rate of approximately 0.9° per 300 feet. When the temperature of the surface soil and of the air is highest, the atmospheric pressure also tends to be at its minimum, so that the air escapes from the soil with greater facility. After the surface soil attains its maximum temperature and then begins to cool, its air contracts, tends to produce a partial vacuum, and consequently draws air from the atmosphere, so that its pressure will be in equilibrium with that of the latter. The fall of temperature is also conducted downward and proceeds as a wave, and as it descends it causes a dimunition in volume at the corresponding depths and therefore produces an inward flow of air. This cold wave, however, is preceded by the maximum temperature wave, which as it proceeds downward causes a further expansion of air, which goes to make up for the decreased volume of air caused by the cold wave following immediately after. The difference in temperature, however, of the soil at any depth immediately before and after the maximum temperature wave is reached is very small, as experiments at this Station show; consequently the expansion and expulsion of air caused by the downward march of the minimum temperature wave is not very appreciable. Hence, as the cold wave proceeds downward and produces a decrease in volume of the soil air, the air that comes to make

up for this decrease, so that an equilibrium of pressure will exist, is mainly from the outside atmosphere. After a certain depth is reached, the maximum temperature wave entirely disappears, and there is no more upward expulsion or movement of air. From now on, as the temperature of the soil is further decreased and the volume of its air diminished correspondingly, the current of flow of air into the soil is entirely from the outside atmosphere. This downward flow of air will continue until the soil temperature begins to rise again and the cycle recommences. When the minimum temperature of the surface soil is reached, it is, as a rule, about the same or slightly higher than that of the air immediately above. The temperature of the air at about this period increases with the height in the same manner as the temperature of the soil increases with depth, which is just the opposite from what it is during the day. This increase instead of decrease of temperature at night with a rise in elevation is called "surface temperature inversion." At this minimum temperature the atmospheric pressure approaches its maximum, and the inward flow of air is thereby facilitated.

All the foregoing facts lead to the enunciation of a general law that during the day, as the temperature rises, the soil air tends to flow outward into the atmosphere, and during the night, as the temperature falls, air from the atmosphere tends to flow inward into the soil. This law diametrically opposes the prevalent theory that during the night there is an upward movement of moist warm air. The above law, however, seems to be borne out by logic and appears to be confirmed by experimental evidence subsequently to be presented. The prevalent theory seems unreasonable; for instance, if it is admitted, which it must be, that the soil air escapes into the atmosphere during the day as the temperature rises, then where and when does the soil obtain its air if it continues to give up air even during the night? It might be argued that it is vapor that is rising to the surface and not air. That is inconceivable in the present case. It is true that distillation would occur if the amplitude of temperature were appreciable and constant, but it has been shown that the temperature of the whole column of soil decreases constantly and that an air current from the cold atmosphere is drawn inward which tends to encounter and oppose any upward movement of vapor rising from any difference in temperature. Moreover, granting for sake of argument that there is a vapor rising from the warmer soil to the colder soil at the surface, the amount would be extremely small—too small to account for the great quantity of dew commonly noted—because the temperature amplitudes of the soil at different depths at night are never very great. In fact, during the spring months, as the temperature of the lower depths continually rises and the trend of the air temperature is upward, the range of temperature between the surface and the lower depths, say 6 inches, is small, usually amounting only to about 2° or 3° C. The greatest differences in temperature at the different depths in the morning occur

in the fall, when the trend of the air temperature is downward and the surface soil temperature continually falls. At this time the variation in temperature between the surface and 6 inches of the mineral soils may be as high as 8° C.

The truth of the matter, however, seems to be that instead of vapor rising from the warmer soil below to the colder soil at the surface, vapor enters the soil from the atmosphere. This is a natural conclusion from the law enunciated that during the day air is exhaled from the soil and during the night air is inhaled from the atmosphere. The amount of moisture that will thus enter the soil will depend upon the quantity of air inhaled and upon its absolute humidity, but, as calculations show, it is extremely small. The water may be abstracted by the dry soil at the surface as the air is drawn in or it may enter unaffected. Thus, it is possible that the moisture lost by the soil during the day by the expulsion of its moist air is partly, if not wholly, regained at night.

What is, then, the source of the water of the dew? The greatest part of it comes from the lower layer of the atmosphere itself by condensation. Some of it comes from the leaves of trees and plants; and a certain amount comes from the soil by capillary and thermal capillary action, as set forth previously.

According to the foregoing consideration, therefore, the notion that "dew is formed from the vapor rising from the warmer soil into a colder atmosphere" is wrong, and those who proposed and adhere to this theory seem to be laboring under a misapprehension of facts.

MOVEMENT OF MOISTURE FROM A MOIST AND WARM COLUMN TO A DRY AND COLD COLUMN OF SOIL AND FROM A MOIST AND COLD COLUMN TO A DRY AND WARM COLUMN OF SOIL

The soil moisture under field conditions exists during the warm period of the year nearly always in a gradient form. During a long drought even the upper surface dries out, either of its own accord or induced by artificial means. This layer of dry soil formed at the surface is known as mulch. To this mulch is ascribed the important function of conserving the moisture in the soil by its ability to reduce evaporation of water at the surface. It accomplishes this conservation of moisture, it is claimed, by producing a change or break in the capillary connections between itself and the moist soil below.

Since, on account of the kinetic energy, the absorptive and adhesive forces of the solid substance decrease with a rise in temperature, the interesting question arose whether the dry mulch with an excessively high temperature would absorb moisture from a moist soil with low temperature, even when the capillary connections were ideal. The desire to secure information upon this important and exceedingly interesting point led to the execution of the following experiments: Brass tubes, as described in the preceding sections, were filled with soil, one half with

dry and the other half with moist soil, and the two columns were separated only by a circular piece of cheesecloth, in order to facilitate the separation of the two columns for moisture-movement determinations.

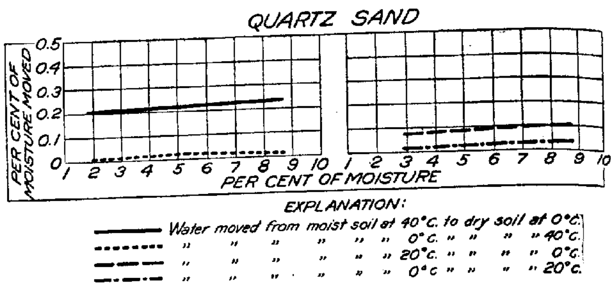

FIG. 5.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of quartz sand, and from a moist and cold to a dry and warm column of quartz sand.

The tubes were then inserted in the boxes shown in figures 1 and 2, and that portion of the tubes containing the moist soil was kept at 20° and 40°, while that part which held the dry soil was maintained at 0° C.

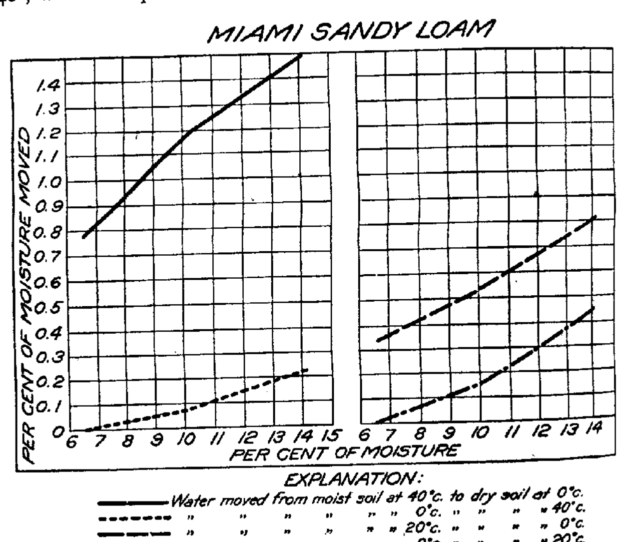

FIG. 6.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of Miami sandy loam, and from a moist and cold to a dry and warm column of Miami sandy loam.

In another set of tubes these temperatures were reversed. The soils employed were the same as those previously described—namely: Quartz sand, light and heavy Miami sandy loam, Miami silt loam, Clyde silt

loam, and Miami clay. There were three different moisture contents used for each soil, designated as low, medium, and high. The duration of all experiments was about eight hours. The numerical data obtained are shown in Table IV. The accompanying figures 5 to 10 represent these same data graphically. Each soil has two charts: The one to the left is for the temperature amplitude of 40°, and the one to the right is for the temperature range of 20° C. The abscissas in every case represent the percentage of moisture content and the ordinates the percentage of water moved either from the moist and warm column to the dry and cold column of soil, or from the moist and cold column to the dry and warm column of soil. The upper curves of each chart represent the

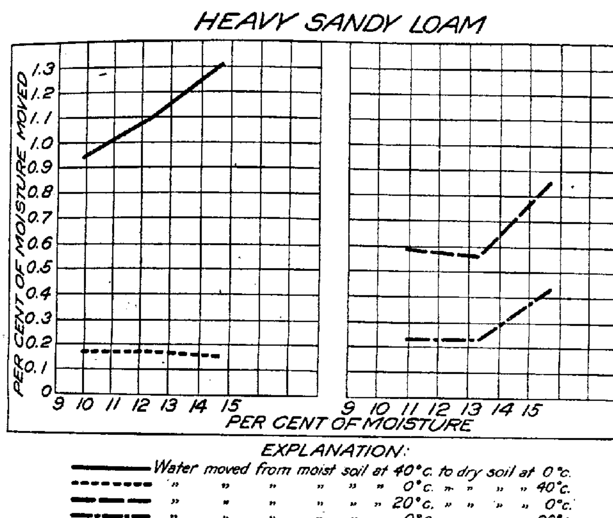

FIG. 7.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of heavy sandy loam, and from a moist and cold to a dry and warm column of heavy sandy loam.

percentage of water movement that took place from the moist and warm soil to the dry and cold soil, while the lower curves show the movement of water that occurred from the moist and cold soil to the dry and warm soil. As in the preceding case, the precentage of moisture moved is based upon the difference in percentages of moisture contained in the dry soil of the beginning and end of the experiment.

Considering first the numerical values showing the amount of water moved from the moist and warm column of soil to the dry and cold column of soil, which are graphically represented by the upper curve of each chart (fig. 5 to 10), it will be seen (1) that this amount is nearly twice as great in the temperature amplitude of 40° as in 20° C., (2) that

it is somewhat greater in soils with higher than with lower colloidal content, and (3) that it increases with the rise in moisture content.

By comparing these results with those obtained with columns of soils of uniform moisture content, some very striking contrasts are revealed. The previous results show, for instance, that the maximum thermal motion of water occurs at a definite but comparatively low moisture content and that the value amounts in some cases to more than 3.50 per cent. The above data show, however, that the maximum movement

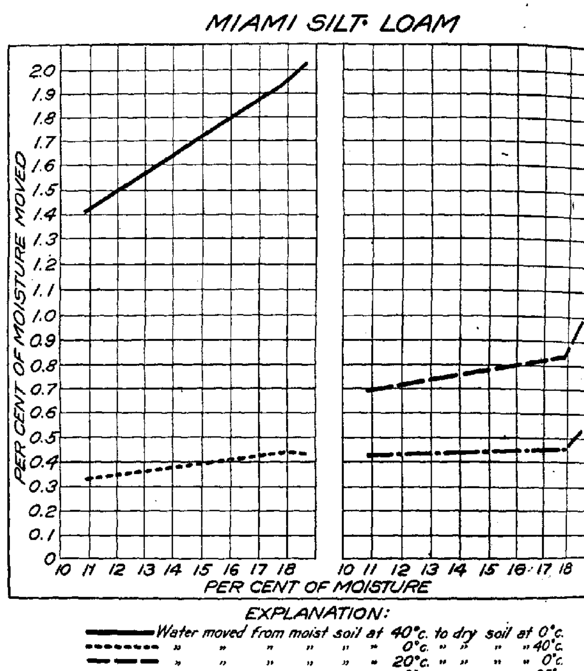

FIG. 8.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of Miami silt loam, and from a moist and cold to a dry and warm column of Miami silt loam.

of water from the moist and warm column to the dry and cold column of soil takes place at the highest water content and that in the majority of cases the percentage of this maximum water translocation is only one-half as great as in the former case.

These apparent differences seem to be easily explainable. The increase of water movement from moist and warm soil to dry and cold soil with a rise in water content is natural and only goes to prove that the water is held by the soil with low moisture content with great force, and consequently it can not be extracted readily and extensively by a greater

abstracting force. When the attractive forces of the soil for water are satisfied and the thickness of the surface and capillary films is increased, then greater quantities of water will be removed by the same abstracting force. The smaller thermal water movement which occurs in the moist and dry soil rather than in the soil of uniform moisture content is due mainly to the cheesecloth which is placed between the dry and moist

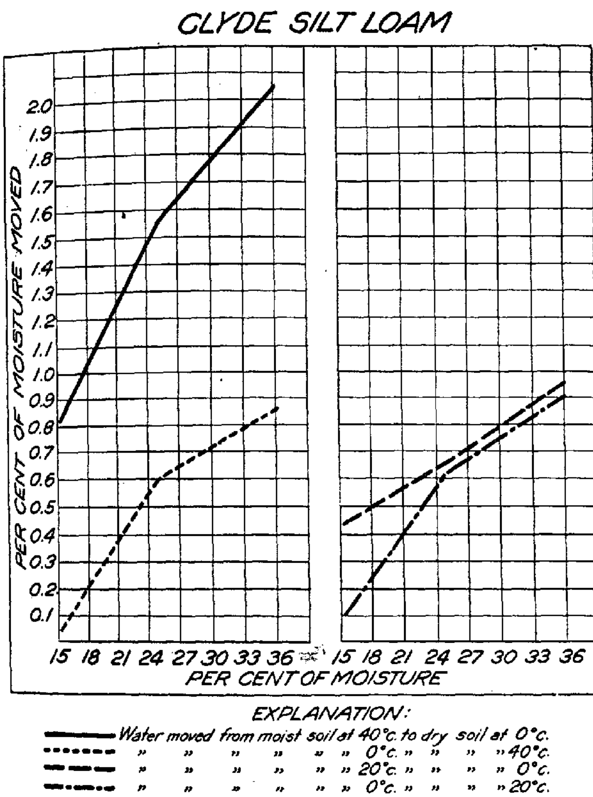

FIG. 9.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of Clyde silt loam, and from a moist and cold to a dry and warm column of Clyde silt loam.

columns of soil. Although this cheesecloth was very thin and had wide meshes, yet it prevented the two columns from forming a complete and perfect contact; consequently the dry soil had to absorb water directly through the cheesecloth as well as from the soil.

Another factor which would seem to impede the rate of water movement from a moist and warm to a dry and cold column of soil is the resistance which the dry soils offer to wetting, owing to the air film

surrounding the particles and to any oily substances that might be present. The influence of this factor, however, must be extremely small, if any, because when these soils were slightly damped the amount of water moved was generally less or about the same as before. The common belief that water moves more rapidly in damp than in dry soils is generally exaggerated. When a soil is damped to eliminate the factor of resistance to wetting, its absorptive power for water is decreased correspondingly, so that one factor tends to counterbalance the other, and at the end the

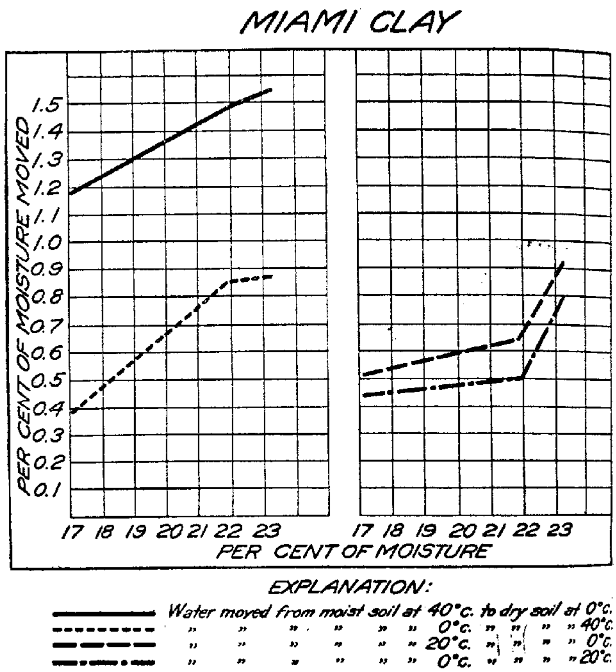

FIG. 10.—Curve showing the percentage of moisture moved from a moist and warm column to a dry and cold column of Miami clay, and from a moist and cold to a dry and warm column of Miami clay.

results are about the same. Moreover, the soils which stubbornly resist wetting are not very common.

From the practical standpoint the results of the second part of the present investigation are probably far more important than those of the first part just discussed. These results show the remarkable fact that when the dry soil is kept at 20° and 40° and the moist soil at 0° C., the dry soil takes up very little, if any, water from the moist soil and that this quantity of water absorbed decreases with a rise in temperature. As will be seen from the data, the percentage of moisture absorbed by the dry soil at 20° is in all cases greater than that absorbed at 40° C.

At both amplitudes of temperature the percentage taken up increases with the colloidal content in the soil, which is natural.

TABLE IV.—*Movement of moisture from a moist and warm column of soil to a dry and cold column of soil and from a moist and cold column of soil to a dry and warm column of soil*

Kind and temperature of soil.	Percentage of moisture in soil.		
Quartz sand:			
At beginning of experiment	1. 85	5. 30	8. 75
Movement from moist column at 20° to dry column at 0° C	. 0746	. 0879	. 1129
Movement from moist column at 0° to dry column at 20° C	. 0105	. 02131	. 03912
Movement from moist column at 40° to dry column at 0° C	. 2048	. 2210	. 2376
Movement from moist column at 0° to dry column at 40° C	. 0121	. 0160	. 01522
Light sandy loam:			
At beginning of experiment	6. 497	10. 141	14. 17
Movement from moist column at 20° to dry column at 0° C	. 345	. 550	. 820
Movement from moist column at 0° to dry column at 20° C	. 061	. 163	. 448
Movement from moist column at 40° to dry column at 0° C	. 779	1. 18	1. 496
Movement from moist column at 0° to dry column at 40° C	. 000	. 08	. 235
Heavy sandy loam:			
At beginning of experiment	9. 906	12. 30	14. 695
Movement from moist column at 20° to dry column at 0° C	. 592	. 569	. 863
Movement from moist column at 0° to dry column at 20° C	. 215	. 211	. 445
Movement from moist column at 40° to dry column at 0° C	. 937	1. 094	1. 309
Movement from moist column at 0° to dry column at 40° C	. 168	. 169	. 150
Silt loam:			
At beginning of experiment	10. 89	17. 88	18. 67
Movement from moist column at 20° to dry column at 0° C	. 687	. 844	. 989
Movement from moist column at 0° to dry column at 20° C	. 411	. 461	. 529
Movement from moist column at 40° to dry column at 0° C	1. 413	1. 942	2. 038
Movement from moist column at 0° to dry column at 40° C	. 347	. 445	. 438
Clyde silt loam:			
At beginning of experiment	15. 349	25. 086	36. 18
Movement from moist column at 20° to dry column at 0° C	. 429	. 662	. 962
Movement from moist column at 0° to dry column at 20° C	. 100	. 606	. 900
Movement from moist column at 40° to dry column at 0° C	. 814	1. 554	2. 046
Movement from moist column at 0° to dry column at 40° C	. 042	. 594	. 852

TABLE IV.—*Movement of moisture from a moist and warm column of soil to a dry and cold column of soil and from a moist and cold column of soil to a dry and warm column of soil*—Continued

Kind and temperature of soil.	Percentage of moisture in soil.		
Clay:			
At beginning of experiment	17.05	21.88	23.29
Movement from moist column at 20° to dry column at 0° C	.514	.653	.923
Movement from moist column at 0° to dry column at 20° C	.436	.502	.796
Movement from moist column at 40° to dry column at 0° C	1.180	1.482	1.552
Movement from moist column at 0° to dry column at 40° C	.380	.850	.873

Obviously, then, the temperature has a tremendous influence upon the absorptive power of soils for water. This is what might be expected from the laws of kinetic energy. According to this law, the energy or motion of the molecules increases with temperature, and consequently the adhesive and absorptive forces of the solid matter for liquids or gases decreases. These results, then, tend to confirm postulate 2 (p. 148), that the attractive forces of the soil for water decrease with a rise in temperature.

The foregoing experimental results and theoretical considerations suggest very strongly that the efficiency of the soil mulches in conserving moisture in the soil is not dependent solely upon their thickness and degree of capillary discontinuity between themselves and the moist soil below, but also upon their temperature. It is well known that the temperature of the surface soils during sun insolation is many degrees higher than that of the air immediately above. In some parts of the world where the sky is clear and the sun insolation very intense, the surface soil may attain a temperature about 40° C. higher than that of the air about 4 feet from the ground. Even at this Station the surface soil temperature of the mineral soils, and especially of the light sandy soils, is very often approximately 15° C. higher than that of the air above. From the surface downward the soil temperature decreases, but in the upper 1 or 2 inches the diminution is far more rapid than at the lower depths, amounting sometimes and in certain soils to more than 11° C. for each inch in depth. When the surface soil is disturbed and a mulch is formed, its heat conductivity is decreased, and the high temperature attained at the surface is not all conducted downward but is compelled to accumulate on the dry mulch and then is radiated back into space. The difference in temperature between the mulch and the moist soil below is sometimes as high as 15° C. at this Station. In arid regions this difference must be far greater.

This excessively greater temperature of the dry mulch diminishes the adhesive and absorptive forces of the dry soil, so that its capacity and intensity to withdraw water from the moist soil below are either entirely prohibited or greatly reduced. The result is that the water is saved from direct evaporation. On the other hand, during the night the soil temperature reverses itself and becomes lowest at the surface and increases with the depth, but the difference between the mulch and moist soil is generally not as great during night as during the sun insolation. Since the attractive and adhesive force of the dry soil and the surface tension of the soil water are increased by the low temperature, the tendency of the soil moisture is to move upward very energetically. To what extent this movement occurs can not be stated with certainty, because the moisture not very far below the mulch is held with a great force and is given up with great reluctancy unless moisture moves from a farther depth below, satisfies the absorptive power, and thickens the surface and capillary films.

Furthermore, the amount of water moved will depend upon the temperature gradient—that is, upon the range of temperature between the surface and lower depths. As already stated, this temperature gradient at night is most marked during the summer and fall and is smallest during the spring. Any water, however, that the mulch pulls up during the night is certain of being evaporated during the day. May it not be, then, that an appreciable amount of water is lost from the soil in this manner?

Temperature not only tends to conserve moisture in the soil after the mulch is formed but also aids and hastens the formation of this mulch. It has been seen that as the temperature of the moist soil at the upper depth increases, the surface tension of the soil water and the adhesive and absorptive forces of the soil decrease. The upward pulling force, therefore, is diminished, and the water is not brought up with sufficient rapidity to keep the upper layers moist, so that a mulch is formed at the top. The diminution of the surface tension of the soil water at or near the surface is very large during the sun insolation and far greater than the increase during the night, because during the sun insolation the soil absorbs heat from the sun very rapidly, and since the soil is a poor conductor of heat the heat is allowed to accumulate at the surface and raise its temperature far above that of the next layers.

The foregoing considerations have been deduced from the experimental data and from the laws of kinetic energy of matter, surface tension of liquids, etc., in their relation to temperature. It is now of great importance as well as of high interest to know whether these deductions can be verified experimentally. The type of experiment which the writer probably would have performed to test out whether or not the temperature does tend to conserve moisture in the soil has

fortunately been performed by Buckingham (5) for another purpose. In his studies on the loss of water under arid and humid conditions, Buckingham endeavored to imitate these two conditions in the laboratory. He placed soil in cylinders 48 inches long and 2½ inches in diameter and provided each cylinder with side tubes at the bottom for the introduction of water. By means of an electric fan he allowed a current of air to be blown over the top surface of the soils. For the arid conditions this current of air was heated without changing its absolute humidity to a temperature of about 50° to 60° F. above the room temperature. To imitate also the high surface temperature of soils under the strong sunshine of arid climates, the top 1½ inches of the cylinders under the hot air was heated by coils surrounding the cylinders to about the same temperature as the hot air. The breeze of about 3 miles per hour was kept going all the time. The heating current was turned on for six

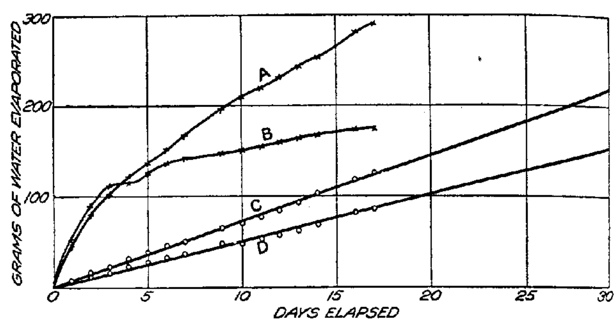

FIG. 11.—Curve showing the evaporation of water from Takoma soil fed with tap water: *A*, Soil under humid conditions; *B*, soil under arid conditions; *C*, water under arid conditions; *D*, water under humid conditions.

hours a day, except on Sundays and holidays. For the humid conditions the soils were placed under the current of air at room temperature. Buckingham performed a number of experiments bearing upon this subject and the results he obtained are qualitatively about the same for all of them. Figure 11 shows a typical set of results.

An examination of figure 11 shows that the loss of water from the soil under arid conditions is much more rapid at first, but after about 4 days have elapsed the rate of loss is less under arid than under humid conditions and continues to be so throughout the duration of the experiment. The rate of evaporation from the soils for the last 10 days is 11.2 inches of rain per year under arid conditions and 51.6 inches of rain per year under humid conditions.

Buckingham explains these results under the supposition that a mulch was formed on the soil kept under arid conditions more rapidly than on the soil kept under humid conditions, and the mulch prevented rapid loss

of water from the former. This explanation is correct, of course, in so far as it represents the result of the mulch, but how this mulch was formed and how it was capable of accomplishing this result he fails to explain correctly. In the opinion of the writer the above results offer an excellent proof that temperature aids and hastens the formation of a mulch, and tends to conserve the soil moisture in the manner previously set forth.

This is a remarkable paradox indeed that a temperature which causes the loss of water should also cause its conservation.

SUMMARY

The main and most important facts presented in the foregoing series of studies may be summarized as follows:

(1) When one half of a column of soil of uniform moisture content is maintained at 20° and 40° and the other half at 0° C. for eight hours the percentage of water moved from the warm to the cold soil increased in all the different types of soil with a rise in moisture content until a certain water content was reached, and then it began to decrease again with further increase in moisture content. The results then plot into a parabola. The percentage of moisture at which the maximum thermal translocation of water occurred is different for the diverse classes of soil, but the percentage of the maximum thermal translocation of water is about the same for all classes of soil for any one of the temperature amplitudes. The percentage of moisture at which this maximum thermal translocation occurred is designated as the "thermal critical moisture content."

These results are contrary to what might be expected from the laws of surface tension and viscosity. They have led to the conclusion that the capillary movement of water in moist soils is not controlled entirely by the curvature of the capillary films, as is generally believed, but also by the unsatisfied attractive forces of the soil for water.

(2) When a moist column of soil was kept at 20° and 40° and a dry column of soil at 0° C. for eight hours and the two columns were separated by an air space, the percentage of moisture distilled over from the moist and warm column to the dry and cold column of soil was very insignificant for both amplitudes of temperature and was about the same for all moisture contents.

These results lead to the conclusion (a) that the amount of water lost from the soil by water vapor is very small; (b) that there is no rising of vapor during the night from the warmer soil below to the cold soil above; and (c) that the water of the dew is not derived from the soil vapor, as is commonly believed.

(3) When a moist column of soil was in contact with a dry column of soil and the former was kept at 20° and 40° and the latter at 0° C. for eight hours the amount of moisture moved from the moist and warm soil

to the dry and cold soil increased with temperature and with moisture content. But when the moist column of soil was maintained at 0° and the dry column of soil at 20° and 40° C. for the same number of hours there was very little, if any, movement of water from the former to the latter.

These results have led to the conclusion that temperature has a very marked influence on the conservation of moisture by mulches.

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SOIL TEMPERATURES AS INFLUENCED BY CULTURAL METHODS

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The data here reported were accumulated under natural field conditions during a period of two years on three plots in a young apple orchard, as follows: (1) Tillage with a cover crop, (2) straw mulch, and (3) grass land. The temperature effect of cultural methods is a detail of a general investigation of the phenomena of orchard soil management. The data have a bearing on other soil problems perhaps important enough to warrant separate presentation at this time.

The temperatures were recorded automatically by means of soil thermographs manufactured by Julien P. Friez & Sons. This instrument consists of a cylinder revolved by an 8-day clock. Blank forms are placed on the cylinder and the temperatures are traced thereon by a pen connected with the thermometer bulb. Temperatures are thus recorded continuously.

The thermometer bulbs were planted 5 or 6 feet northeast of each tree and at a depth of 9 inches. On the straw-mulch plot the bulb was placed under and 12 inches from the outer edge of the mulch collar. Only one instrument was used on each plot. It is felt, however, that the records are trustworthy and portray with reasonable exactness the existing conditions. All instruments were carefully checked with a standard thermometer at the beginning and during the course of the experiment, and their behavior was highly satisfactory. Great care was exercised in changing the chart sheets, to see that each blank was properly placed.

The plots are located on a glaciated, rough, river-bluff, upland soil in southern Indiana. The rocks of the region are limestone, which outcrop on the steeper hillsides. The mechanical analysis shows the soil to be a clay silt. (See Table I.)

TABLE I.—*Mechanical analysis of upper 9 inches of soil on the experimental plots* [a]

Plot.	Fine gravel (2 to 1 mm.).	Coarse sand (1 to 0.5 mm.).	Medium (0.5 to 0.25 mm.).	Fine sand (0.25 to 0.1 mm.).	Very fine sand (0.1 to 0.05 mm.).	Silt (0.05 to 0.005 mm.).	Clay (0.005 to 0 mm.).
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
A.......	0.1	0.7	0.8	1.3	1.8	82.1	13.0
C.......	.2	.8	.9	1.4	5.2	78.7	12.5
D.......	.2	.7	.8	1.6	7.3	77.0	12.4

[a] These analyses were made by the Bureau of Soils, United States Department of Agriculture.

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Plot A received clean cultivation with a rye cover crop sown in late summer and turned under in the spring. The average depth of plowing has been 7 inches. Cultivation started in 1913 on May 1 and in 1914 on May 11. Rye at the rate of 1½ bushels per acre was sown for a cover crop on August 20 in 1913 and on August 15 in 1914. The land was cultivated seven times each season.

Plot C was in grass, which was cut and allowed to lie where it fell, as in plot D, but in addition a mulch of wheat straw was applied about the same time that plot A was plowed, using one bale to a tree. The bales averaged 93 pounds in weight. The litter was scattered around the trees, forming a collar 12 to 14 feet in diameter.

Plot D was in grass, which was cut and allowed to lie where it fell. In the autumn of 1912 plot D was seeded to a mixture of grasses in which timothy largely predominated and may here be considered as a timothy meadow. The grass was mowed for the first time in the middle of June, 1913, largely to prevent weeds from seeding, as the amount of mulch was negligible. The extremely dry summer of 1914 was disastrous to grass, and a cutting on July 10 returned to the land only one-fifth of a ton of dry hay per acre.

Space does not permit the publication of the complete temperature records, but the weekly maximums and minimums are given in Table II. It will be seen that in April plot A began to forge ahead in holding the highest minimum temperature, with plot D second and C third. This condition prevailed until in the fall, when plot A cooled off quickly and D less quickly, leaving C with the highest minimum temperature until spring. The differences, however, in winter temperatures between the plots were small. During the week of February 23, 1913, plot A showed a minimum temperature of 32° F. and plots C and D, 32.5° F. Plot A continued to cool, until during the week of March 16 it reached 32°, when plot D registered its lowest, 31°, and plot C was 33° F. The following winter the three plots reached their minimum temperatures during the week of January 11, that of plot A being 31°; D, 32.5°; and C, 34° F.

TABLE II.—*Records of soil temperatures under different cultural methods, May, 1913, to May, 1915*

PLOT A: TILLAGE WITH COVER CROP

Week ending—		Minimum.	Maximum.	Week ending—		Minimum.	Maximum.	Week ending—		Minimum.	Maximum.
		°F.	°F.			°F.	°F.			°F.	°F.
May	5	45.0	58.5	June	16	58.5	68.0	July	28	67.0	76.0
	12	53.0	60.0		23	67.0	74.0	Aug.	4	72.0	80.0
	19	53.0	63.0		30	67.5	78.0		11	70.0	77.5
	26	54.0	63.0	July	7	73.0	80.5		18	71.0	78.0
June	2	54.5	66.5		14	69.0	77.5		25	66.0	77.0
	9	60.0	69.0		21	69.0	77.5	Sept.	1	66.0	73.0

TABLE II.—*Records of soil temperatures under different cultural methods, May, 1913, to May, 1915*—Continued

PLOT A: TILLAGE WITH COVER CROP—continued

Week ending—		Minimum.	Maximum.	Week ending—		Minimum.	Maximum.	Week ending—		Minimum.	Maximum.
		°F.	°F.			°F.	°F.			°F.	°F.
Sept.	8	68.0	76.5	Mar.	30	33.0	50.0	Oct.	19	56.0	60.0
	15	59.0	75.0	Apr.	6	41.0	51.0		26	53.0	60.0
	22	55.5	66.0		13	38.0	46.0	Nov.	2	45.0	57.5
	29	51.0	61.0		20	42.5	55.5		9	45.0	53.0
Oct.	6	55.0	63.0		27	44.0	61.5		16	43.0	52.0
	13	54.0	65.0	May	4	51.5	66.0		23	34.0	46.0
	20	50.0	59.0		11	52.5	63.0		30	33.0	45.0
	27	43.5	51.0		18	52.5	64.0	Dec.	7	43.0	50.5
Nov.	3	......	......		25	56.0	67.0		14	37.0	43.0
	10	41.0	48.0	June	1	64.0	74.0		21	34.5	37.0
	17	37.0	48.5		8	65.5	73.5		28	34.0	35.0
	24	45.0	56.0		15	70.0	77.0	Jan.	4	32.0	33.5
Dec.	1	43.0	52.5		22	67.0	74.0		11	31.0	32.0
	8	43.0	53.0		29	68.0	79.0		18	31.0	32.0
	15	36.0	42.0	July	6	65.0	75.5		25	32.0	33.0
	22	36.0	41.0		13	70.0	80.0	Feb.	1	33.0	34.0
	29	36.0	37.0		20	68.0	78.0		8	33.0	36.0
Jan.	5	35.0	36.0		27	70.0	80.0		15	32.0	45.0
	12	34.0	35.0	Aug.	3	71.0	79.0		22	35.0	40.0
	19	33.0	34.0		10	72.0	78.0	Mar.	1	35.0	47.0
	26	33.0	37.0		17	70.0	77.5		8	34.0	37.0
Feb.	2	34.0	46.5		24	70.0	80.0		15	35.0	41.0
	9	34.0	40.0		31	66.5	74.5		22	36.0	40.0
	16	33.0	34.0	Sept.	7	64.0	74.5		29	35.0	41.0
	23	32.0	33.0		14	59.5	72.0	Apr.	5	35.0	42.0
Mar.	2	31.0	33.0		21	61.5	73.5		12	40.0	52.5
	9	31.0	32.0		28	57.0	74.0		19	44.0	55.0
	16	30.0	32.5	Oct.	5	58.0	64.5		26	50.0	66.0
	23	31.0	34.0		12	59.0	67.5	May	3	57.0	60.0

PLOT C: STRAW MULCH

May	5	47.0	53.0	Oct.	6	58.0	61.0	Mar.	9	33.0	34.0
	12	50.0	53.0		13	57.0	61.5		16	33.0	33.5
	19	50.0	56.0		20	51.5	58.5		23	33.0	34.0
	26	55.0	57.0		27	50.0	54.0		30	33.0	37.0
June	2	56.0	60.0	Nov.	3	....	....	Apr.	6	37.5	42.0
	9	58.5	61.5		10	45.0	48.0		13	38.0	43.0
	16	57.0	60.0		17	42.0	47.0		20	40.0	48.0
	23	60.0	65.0		24	46.0	51.5		27	44.5	49.5
	30	64.0	70.0	Dec.	1	47.0	51.0	May	4	49.0	51.5
July	7	68.0	71.0		8	46.5	51.0		11	51.0	52.5
	14	67.0	69.0		15	41.0	47.0		18	51.0	54.5
	21	68.0	71.0		22	39.5	42.5		25	52.0	55.0
	28	66.0	68.5		29	38.0	40.0	June	1	56.0	59.5
Aug.	4	68.0	70.0	Jan.	5	37.5	38.5		8	58.0	62.0
	11	66.0	70.0		12	36.0	39.0		15	63.0	65.0
	18	70.0	72.0		19	34.0	36.0		22	60.5	64.0
	25	68.0	72.0		26	36.0	38.0		29	64.0	67.0
Sept.	1	66.0	69.0	Feb.	2	37.0	41.5	July	6	63.0	65.0
	8	66.0	70.0		9	35.0	39.0		13	64.0	67.5
	15	62.0	69.0		16	34.0	35.0		20	66.0	68.0
	22	61.0	64.5		23	32.5	35.0		27	66.0	69.0
	29	57.5	61.0	Mar.	2	33.0	34.0	Aug.	3	65.0	70.0

TABLE II.—*Records of soil temperatures under different cultural methods, May, 1913, to May, 1915*—Continued

PLOT C: STRAW MULCH—continued

Week ending—	Minimum.	Maximum.	Week ending—	Minimum.	Maximum.	Week ending—	Minimum.	Maximum.
	°F.	°F.		°F.	°F.		°F.	°F.
Aug. 10	65.0	67.5	Nov. 9	51.0	52.5	Feb. 8	35.0	37.0
17	65.0	68.5	16	48.5	52.0	15	35.0	39.0
24	66.0	68.5	23	40.0	50.0	22	36.0	38.5
31	65.0	68.0	30	41.0	45.0	Mar. 1	36.0	40.0
Sept. 7	64.0	67.5	Dec. 7	45.5	47.5	8	36.0	37.0
14	61.5	66.0	14	43.0	46.0	15	36.0	37.0
21	61.5	64.0	21	38.0	43.0	22	37.0	38.0
28	59.0	65.0	28	36.0	38.5	29	36.5	38.0
Oct. 5	58.0	60.0	Jan. 4	35.0	37.0	Apr. 5	35.5	37.0
12	60.0	62.5	11	34.0	36.0	12	38.0	45.0
19	58.0	60.0	18	35.0	36.0	19	42.0	45.0
26	51.0	56.0	25	35.0	36.5	26	45.0	53.0
Nov. 2	56.0	58.0	Feb. 1	35.0	36.0	May 3	52.0	55.0

PLOT D: GRASS LAND

Week ending—	Minimum.	Maximum.	Week ending—	Minimum.	Maximum.	Week ending—	Minimum.	Maximum.
May 5	44.5	57.5	Jan. 5	36.0	37.0	Sept. 7	63.0	70.0
12	48.5	59.0	12	35.5	37.0	14	60.0	67.5
19	49.0	62.0	19	33.5	36.5	21	60.0	66.0
26	53.0	62.5	26	33.0	36.5	28	56.0	66.5
June 2	53.5	66.0	Feb. 2	35.0	44.0	Oct. 5	55.0	60.0
9	58.0	67.0	9	35.0	39.5	12	58.0	62.5
16	57.0	69.0	16	34.0	36.0	19	56.0	58.0
23	66.0	74.0	23	32.5	35.0	26	54.0	56.5
30	65.0	76.5	Mar. 2	32.0	35.0	Nov. 2	46.0	53.0
July 7	70.0	78.5	9	32.0	34.0	9	47.0	51.0
14	67.5	76.0	16	31.0	34.0	16	44.0	50.0
21	....	....	23	33.0	34.0	23	37.0	47.0
28	....	....	30	32.0	46.0	30	35.0	44.0
Aug. 4	69.0	76.0	Apr. 6	40.0	48.0	Dec. 7	44.0	47.5
11	67.0	74.5	13	37.5	44.0	14	40.0	44.0
18	68.0	74.0	20	41.0	53.0	21	35.5	41.0
25	64.0	73.5	27	44.0	57.0	28	34.5	36.5
Sept. 1	62.5	68.5	May 4	50.5	61.0	Jan. 4	35.0	37.0
8	64.0	69.5	11	52.0	58.5	11	32.5	35.0
15	57.5	69.0	18	53.0	60.5	18	33.0	34.0
22	55.5	62.5	25	54.0	62.0	25	33.5	35.5
29	51.0	57.0	June 1	60.5	67.0	Feb. 1	33.0	35.0
Oct. 6	52.5	59.5	8	60.5	69.0	8	33.0	35.0
13	52.0	60.0	15	65.0	71.0	15	32.5	38.5
20	49.0	56.0	22	63.5	70.0	22	33.0	38.0
27	43.0	47.0	29	67.5	73.5	Mar. 1	35.0	41.0
Nov. 10	41.5	47.0	July 6	63.5	72.0	8	33.0	35.0
17	39.0	49.0	13	68.0	76.0	15	33.5	36.5
24	45.0	54.0	20	67.0	75.0	22	35.0	37.0
Dec. 1	43.5	51.5	27	68.0	77.0	29	35.0	38.0
8	44.0	52.0	Aug. 3	68.0	74.0	Apr. 5	34.0	38.0
15	36.5	44.5	10	69.0	74.0	12	37.0	47.5
27	36.5	41.0	17	67.0	73.5	19	42.5	48.0
29	36.5	37.0	24	68.0	75.5	26	46.0	58.0
			31	65.0	71.0	May 3	53.0	59.0

Plot A maintained the highest maximum temperature during the spring and summer and until quite cold weather in the fall, when plot C registered the highest maximum temperature. This lasted for a month or so during the coldest weather, and as soon as it began to moderate in late winter plot A warmed up rapidly, with D next.

The greatest variation between plots occurred during the summer months. In the spring and fall there is a transition period in which the temperature differences are less. During the summer of 1913 plot A registered a maximum temperature of 80.5° the week of July 7, when plot D was 78.5°, and plot C was 71° F. However, plot C later, the week of August 18, registered a maximum temperature of 72° F. During the week of July 13, the following summer, plot A registered a maximum of 80°; plot D, 77°, the week of July 24; and plot C, 70° F., the week of August 3.

Figures 1 to 4 are reproductions of typical seasonal charts of soil temperatures prevailing under the three cultural systems. These give an idea of the diurnal variations. During the winter the temperatures are quite constant from day to day, with very little variation between plots (fig. 1). In the spring the diurnal range is considerable in the plot under tillage with cover crop and the grass land, but varies little under the straw mulch, which exhibits a very gradual warming up (fig. 2). During the summer season, fluctuations become quite pronounced under tillage and grass, but the straw mulch still maintains its uniformity (fig. 3, *C*). During the season of greatest daily range the maximum and minimum temperatures occur about 10 p. m. and 10 a. m., respectively (fig. 3, *A* and *D*). In the fall the temperatures and ranges are not radically different from those of spring, except that the general trend of temperatures is reversed (fig. 4).

In conclusion, it may be said that a system of clean cultivation with a winter cover crop is characterized by extreme diurnal and annual fluctuations in soil temperature; that a straw mulch equalized these fluctuations to a marked extent, as does also a grass crop, though in less degree.

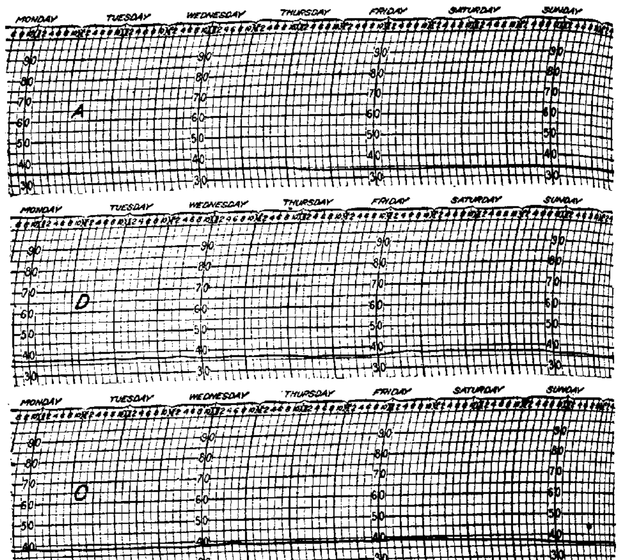

FIG. 1.—Typical charts of soil temperatures during the winter season: Records for week ending January 12, 1914. *A*, Tillage with cover crop; *D*, grass land; *C*, straw mulch.

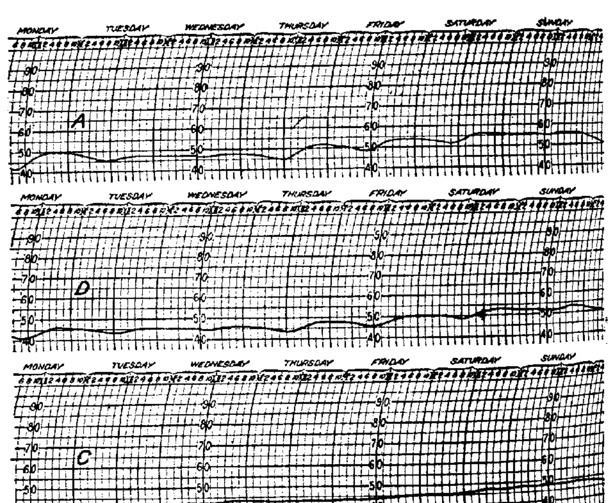

FIG. 2.—Typical charts of soil temperatures during the spring time: Records for week ending April 23, 1914. *A*, Tillage; *D*, grass land; *C*, straw mulch.

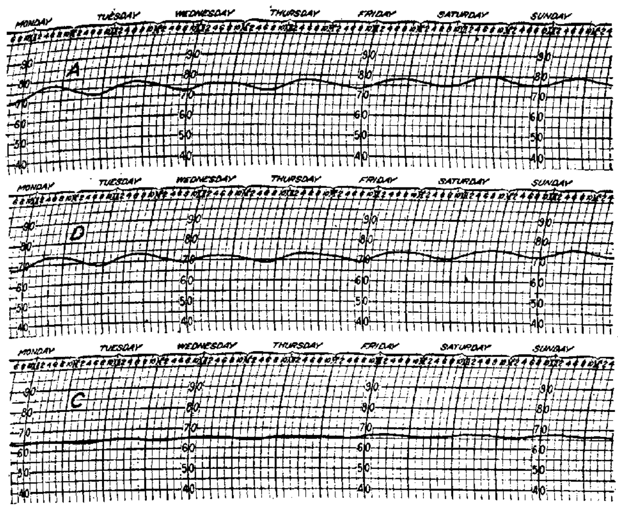

Fig. 3.—Typical charts of soil temperatures during the summer months: Records for week ending June 13, 1914. *A*, Tillage; *D*, grass land; *C*, straw mulch.

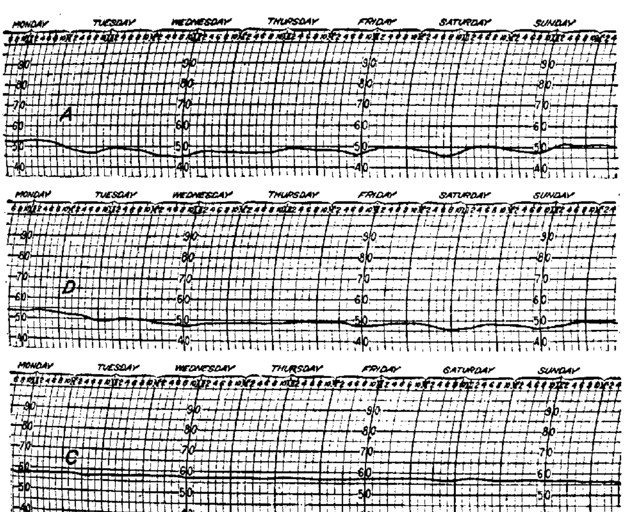

Fig. 4.—Typical charts of soil temperatures during the fall of the year. Records for week ending November 2, 1914. *A*, Tillage with cover crop; *D*, grass land; *C*, straw mulch.

ALTERNARIA PANAX, THE CAUSE OF A ROOT-ROT OF GINSENG

By J. ROSENBAUM, *Specialist in Phytophthora*, and C. L. ZINNSMEISTER, *formerly Agent, Cotton and Truck Disease Investigations, Bureau of Plant Industry*

While working with diseases of ginseng (*Panax quinquefolium*) during the summer of 1913, the authors obtained from a garden near Cleveland, Ohio, roots which showed a peculiar dry-rotted condition about the crown. The dark-brown center of the lesion characterizing this dry-rot was more or less sunken and firm to the touch and gradually shaded into the yellowish white color of the healthy root. It is distinguished from other root-rots by its lack of odor and the fact that the rotted roots never become soft. Plate XII is a reproduction of a photograph of three roots showing the typical lesions of the disease.

When the rot is near the crown of the root, the top of the plant often shows signs of the disease. These signs are a wilting and yellowing of the leaves, which on being disturbed drop off readily at the point of attachment to the main stalk. Such a condition may, however, be caused by other root-rots attacking ginseng, as, for example, the rot caused by *Phytophthora cactorum*.

Because of the unusual character of these lesions, numerous isolations were made from them, and in all cases an Alternaria-like fungus closely resembling *Alternaria panax* Whet. was secured in pure culture. In order to determine whether these two fungi were identical, a series of inoculations on roots and tops were made with both cultures. In addition, a study was made of their macroscopic and microscopic appearance. This work was begun during the summer of 1913 in Ohio and repeated during the summer of 1914 in New York.

In the main two methods of inoculation were followed. Healthy roots were taken from the garden, washed, freed from their fiber roots, sterilized for 10 minutes in a 1 to 1,000 solution of mercuric chlorid, washed in sterile distilled water, and placed in sterilized test tubes. The roots were then injured by making an incision in them with a sterile scalpel, and in this incision was placed a small portion of the fungus from a pure culture. Roots treated in the same way but not inoculated were used as checks. Six series of inoculations were made in this manner, using the Alternaria-like fungus isolated from dry-rotted roots. Ninety-five per cent of infection was secured, and the checks in all cases remained healthy. Typical lesions (Pl. XII) were produced in every instance. In no case did the rotted condition involve the entire root. The time necessary after inoculation for the lesion to appear varied from seven to nine days. Once established the progress of the rot was also very slow.

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At the time the above series were being run, five series of similar inoculations were made with a pure culture of *Alternaria panax*, the necessary checks for each series being used. One hundred per cent of infection was obtained with this fungus, the symptoms and lesions resulting from the inoculation being in every case similar to and indistinguishable from those obtained with the Alternaria-like fungus. Plate XIII, figure 1, shows a longitudinal section through one inoculated root.

In order to test further the pathogenicity of these fungi and to confirm their identity, inoculations were made directly in the soil on roots to which the tops were still attached. Six series were made with the Alternaria-like fungus and five with *Alternaria panax*. The soil was removed from around the crown of the roots and an incision was made in the crown. Into this incision was placed the inoculating material from pure cultures of the two fungi. Ninety-two per cent of infection resulted from the Alternaria-like fungus and eighty-five per cent from *Alternaria panax*. The symptoms and lesions were again characteristic and similar in each case.

Further inoculations were made on the tops by inoculating the leaves with mycelium from pure cultures of both fungi. For some unexplainable reason, or owing to the plants having been sprayed with Bordeaux mixture, no definite results were secured during the summer of 1913. In June, 1914, the work was repeated. Typical leaf-spots of *Alternaria panax* were produced in abundance with both fungi. Plate XIII, figure 2, is a reproduction of a photograph of the lesions produced on ginseng leaves with the species of Alternaria isolated from roots. Spores from these spots were secured and examined. No differences could be noted.

Reisolations were made from the inoculated roots and leaves, and a fungus identical with the original one used for inoculating was obtained.

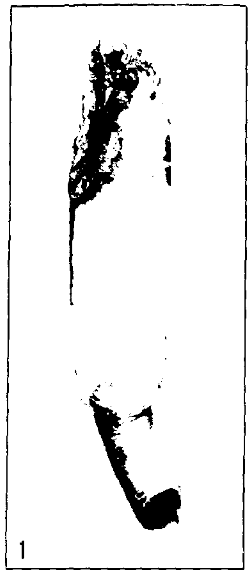
Numerous attempts to produce infection on the roots without previously injuring them gave only negative results.

Inasmuch as these fungi show no cultural differences and as both are able to infect the leaves and roots of the ginseng plant, the only conclusion warranted by the data at our disposal is that they are identical. This being the case, the blight problem confronting the ginseng grower becomes more complicated. Heretofore it has not been supposed that *Alternaria panax* is able to cause a rot of the root.

The above facts warrant the ginseng grower in taking other means besides spraying in the control of this disease. The means recommended, in addition to spraying, are (1) care in transplanting so as to injure the roots as little as possible, (2) the removal of all tops and stems in the fall, and (3) where the crowns of the roots are sufficiently deep below the surface of the soil, burning over the surface of the bed with a thin layer of straw after the tops have been removed.

PLATE XII

Lesions on ginseng roots due to *Alternaria panax*.



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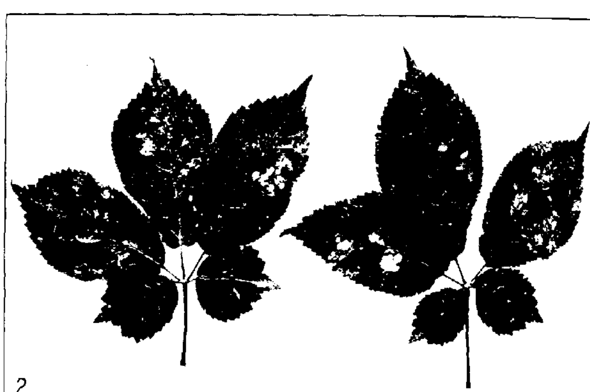

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PLATE XIII

Fig. 1.—Longitudinal section of ginseng root showing the results of inoculation with *Alternaria panax*.

Fig. 2.—Inoculations on ginseng leaves with the species of Alternaria isolated from ginseng roots.

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